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Final state QCD corrections to off-shell single top production in hadron collisions.

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Abstract

In this paper I study final state QCD radiative corrections to off-shell single top production via decaying W at hadron collider energies. With respect to the narrow width approximation, taking into account the widths of the particles lowers the cross section, but QCD corrections to Γ_{top} enhance it. The tree level Breit-Wigner distribution of the produced top invariant mass is distorted by final state QCD radiation, while the peak position remains unchanged.

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1 Introduction

The discovery of the top quark at CDF and D0 [1], has opened a new era of measurements in top-quark physics. Now, the properties of the top quark can be directly investigated, not only inferred from their effects in radiative corrections.
At hadron colliders, the dominant production mechanisms are, of course, the $t\bar{t}$ channels

$$
\begin{aligned}
q\bar{q} &\to t\bar{t} \\
gg &\to t\bar{t}\,,
\end{aligned} \tag{1}
$$

but single top quarks events are also present, such as

$$
\begin{aligned}
& q'\,g\,(W^+\,g) \to q\,t\,\bar{b} \\
& q'\,b \to q\,t \\
& q'\,\bar{q} \to W^* \to t\,\bar{b} \\
& g\,b \to W^- t\,.
\end{aligned} \tag{2}
$$

The first two mechanisms are known as W-gluon processes [2], the third one as W^* production [3] and the fourth one as Wt production [4]. The cross sections in eq.(2) are ordered according to their magnitude in $p\bar{p}$ collisions at $\sqrt{s} =$ 2 TeV for $m_t =$ 176 GeV [5].
Even with less expected events, single top production processes are important because they provide a consistency check on the measured parameters of the top quark in $t\bar{t}$ production.

Radiative corrections to the processes in eq.(1) and eq.(2) are well known in the literature [6], but usually, performed in the narrow width approximation, in which production and decay of the top are treated independently. Using this approximation makes of course life easier, but a check on its validity is still missing.
Since, in the narrow width approach, diagrams connecting decaying products with the production process are missing, one especially expects deviations due to a non exact treatment of the gluonic radiation, which is an important quantity for the reconstruction of m_t in $t\bar{t}$ events [7]. Therefore a precise study of it, even in a simpler case, can give hints on its relevance in the main production mechanisms of eq.(1).

For those reasons, I decided to perform a complete calculation of the final state QCD radiative corrections to W^* single top production, taking into account all the subsequent decays. Among all the others, the W^* mechanism is interesting because possible new physics may introduce a high mass state (say particle V) to couple strongly with the $\bar{t}b$ system such that the production rate from $q'\bar{q} \to V \to t\bar{b}$ can deviate from the standard model W^* rate [5, 8]. Therefore accurate predictions of the standard properties of the top in this channel are also important by themselves.
The background QCD contribution is known [3], so I 'll study here the QCD one loop corrections to the signal diagram of fig. 1. For this process, thanks to the color structure, initial and final state QCD corrections do not interfere and are separately gauge invariant, so that, in order not to obscure the effects I want to study, I decided, in this paper, to concentrate my attention on final state gluonic corrections. Initial state corrections are however very simple and a study including them will be treated elsewhere [9]. I chose the semi leptonic final state $\nu_l\ l^+\ b\ \bar{b}$ because it is easier to detect experimentally. The extension to $q'\ \bar{q}\ b\ \bar{b}$ is anyway trivial. In fact, diagrams with gluons connecting b or $\bar{b}$ with q' or $\bar{q}$ are killed, at the one loop level, by the color factor, so one is left with simple gluonic corrections for the $W\, q'\, \bar{q}$ vertex.

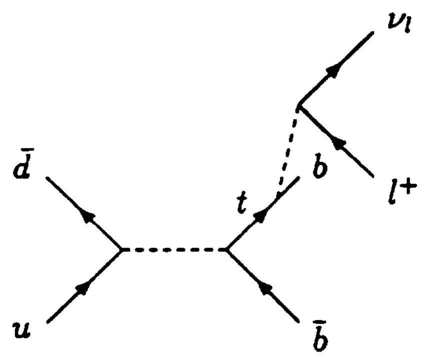

Figure 1: *Tree level diagram for $\bar{d}\ u \to \nu_l\ l^+\ b\ \bar{b}$ via single top production. Here, and in the following figures, dashed lines denote W's.*

2 The calculation

The tree level diagram for the process is drawn in fig.1, while in fig. 2 and 3 I show the one loop virtual diagrams and the real bremsstrahlung.

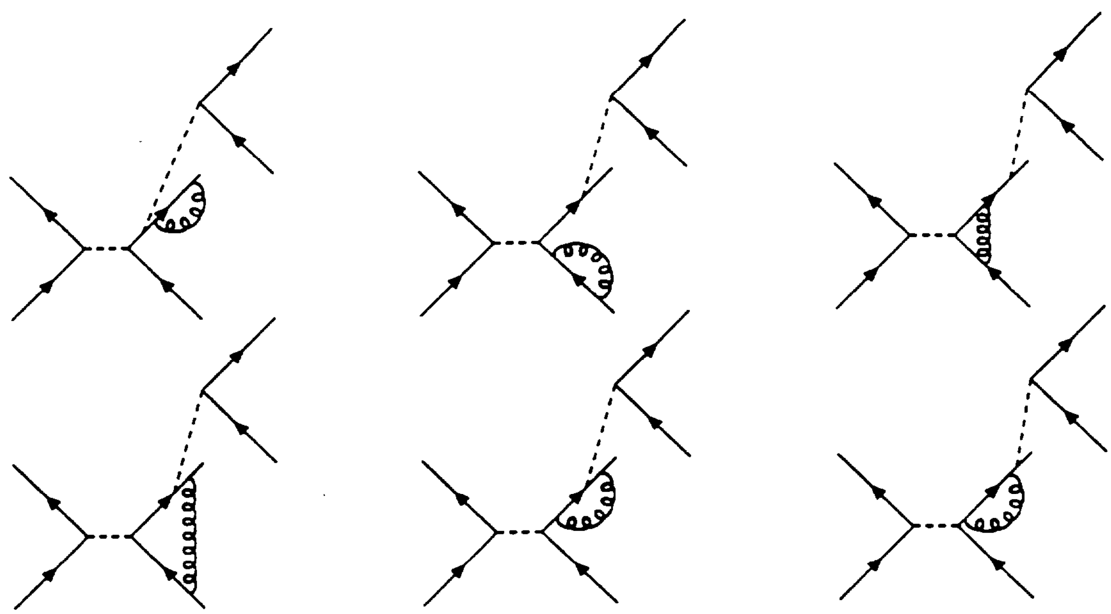

Figure 2: *Final state one loop QCD virtual diagrams.*

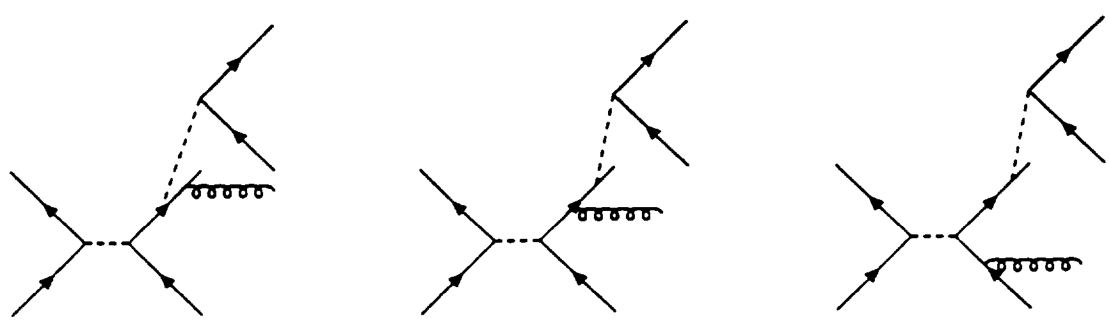

Figure 3: *Real gluon emission.*

I computed the virtual corrections using standard Passarino-Veltman techniques [10], with the help of the Symbolic Manipulation program FORM [11]. I used dimensional regularization for ultraviolet, collinear and soft divergences. Furthermore, I kept everywhere complex masses for top and W, but I systematically neglected the bottom mass.
An analytic approximation in n dimensions for the soft-collinear part of the real emission was built following ref. [12] and the cancellation of all diver-

gences performed analytically.
Both the virtual and the real contributions have been computed applying helicity amplitudes methods [13], and the final expressions implemented in a Monte Carlo program [9], that uses the self-optimization techniques of ref. [14]. Since those techniques are applied here, for the first time, in loop calculations, it may be useful to briefly discuss the adopted strategy. More details will be found in ref. [9].

The problem here is the matching between hard and soft phase space. Schematically, the final result for the cross section σ_{tot} (with any kind of cut) can be written as a sum of four contributions

$$\sigma_{tot} = \sigma_0 + \sigma_V + \sigma_S(\delta) + \sigma_H(\delta) \tag{3}$$

where σ_0 is the lowest order result, σ_V the virtual contribution and σ_S, σ_H the soft and hard real radiation.
The sum, $\sigma_V + \sigma_S(\delta)$ does not contain soft and collinear singularities, on the other hand $\sigma_S(\delta) + \sigma_H(\delta)$ is independent on δ, where δ is the separation between soft and hard gluons (following again ref. [12], δ in a cut on the invariant mass of $g\ +\ b$ and $g\ +\ \bar{b}$). The last statement is true only if an *exact* computation of $\sigma_S(\delta)$ is performed. Instead, what one usually does is computing $\sigma_S(\delta)$ for small δ. In such a limit, because of factorization properties ([12, 15]), very simple expressions are obtainable in terms of the born result multiplied by universal coefficients containing $\log(\delta)$ and $\log^2(\delta)$. At this point, by numerically going to the limit $\delta \to 0$, one gets unbiased results. Of course, if δ is too small, large numerical cancellations take place between $\sigma_S(\delta)$ and $\sigma_H(\delta)$, resulting in large errors in the Monte Carlo integration. A good value for δ can be usually found by numerically checking the independence on δ of the results.
For fixed δ one would like to know how many Monte Carlo points have to be spent to separately compute all four contributions in eq.(3), mainly because usually the most time consuming part is σ_V, that contains loop diagrams. This is a typical problem that can be solved using the Multichannel self-optimizing approach of ref. [14]. One starts with the same amount of points for all channels and, during the run, the Monte Carlo self-adjusts itself, so that afterwards one usually obtains a smaller percentage of the computational time spent in the evaluation of σ_V, which means a better estimate of σ_{tot} in a shorter time.

channel	percentage before opt.	percentage after opt.
1	0.2	0.0996
2	0.2	0.5436
3	0.2	0.1265
4	0.2	0.2083
5	0.2	0.0220

Table 1: *Percentage of the Monte Carlo points used for each channel in the evaluation of σ_{tot} before and after the self-optimization. The first three channels take care of the peaking structure of σ_H given by the Feynman diagrams in fig. 3, channel 4 refers to $\sigma_0 + \sigma_S$ and channel 5 to σ_V.*

In table 1 I show a typical result of the self-optimization procedure.

I made several checks on the final result. First of all, I verified that the CP invariance of the tree level current

$$T_{\alpha\mu} = \bar{u}(b)\,\gamma_\alpha(1-\gamma_5)(\not{p}_{l^+} + \not{p}_{\nu_l} + \not{p}_b + m_t)\gamma_\mu(1-\gamma_5)\,v(\bar{b}) \tag{4}$$

remains after QCD loop corrections. Then, by numerically rescaling Γ_W, Γ_t and the cross section by the same amount, I checked the agreement between the Monte Carlo estimate of the total $\mathcal{O}(\alpha_s)$ $t\bar{b}$ on-shell cross section (σ_{MC}) and (for example) the analytic result (σ_{AN}) of ref. [16] (see table 2). I also tested, for small δ, the independence on δ of the results. All numbers in this paper are obtained with $\delta = 0.2\,GeV^2$.

A last comment is in order. Taking into account the widths of the decaying particles gives rise to conceptual problems with respect to the gauge invariance. The correct gauge invariant prescription would be to compute the widths as the imaginary part of the one loop renormalized propagators and all set of relevant loop diagram necessary to restore gauge invariance. Since, in the process at hand, W and t decay via electroweak interactions, this would imply to include terms of the one loop $\mathcal{O}(\alpha)$ calculation at the tree level and part of the two loop $\mathcal{O}(\alpha\alpha_s)$ corrections in the $\mathcal{O}(\alpha_s)$ contribution. Since I am interested here in $\mathcal{O}(\alpha_s)$ corrections, the neglected $\mathcal{O}(\alpha)$ terms are expected to be small, so I followed the naive prescription of considering everywhere constant complex masses.

$\sqrt{s}$ (GeV)	σ_{MC} (pb)	σ_{AN}
300	0.09086 ± 0.00002	0.09088
	0.10499 ± 0.00035	0.10547
600	0.03508 ± 0.00001	0.03507
	0.03784 ± 0.00027	0.03774
900	0.01653 ± 0.00001	0.01653
	0.01763 ± 0.00019	0.01748
1200	0.00948 ± 0.00001	0.00948
	0.00999 ± 0.00014	0.00996
1500	0.00612 ± 0.00001	0.00612
	0.00643 ± 0.00010	0.00640
1800	0.00427 ± 0.00001	0.00427
	0.00454 ± 0.00007	0.00446

Table 2: *Comparison between the Monte Carlo total cross section, in the limit of vanishing widths, and the analytic on-shell calculation. No convolution with the parton densities has been performed. The first entry is the tree level result. In the second entry all final state QCD corrections are included.* $m_t = 176\,GeV$ *and* $\alpha_s = 0.12$.

3 Results

In this section, I present some results for the process $\bar{d}\,u \to \nu_l\, l^+\, b\, \bar{b}$ obtained with the Monte Carlo of ref. [9]. I chose to plot three useful distributions for measuring the top mass in $p\bar{p}$ collisions at $\sqrt{s} = 2\ TeV$, namely the total hadronic transverse energy (H_T), the invariant mass $\sqrt{(p_{l^+} + p_b)^2}$ (m_{bl}) and the "top mass distribution" $\sqrt{(p_{\nu_l} + p_{l^+} + p_b)^2}$ ($m_{bl\nu}$). Of course, due to the presence of an undetected neutrino, the last quantity is not going to be easy to reconstruct experimentally. However, $m_{bl\nu}$ is of theoretical interest and directly measurable in the channel $q'\,\bar{q}\,b\,\bar{b}$.
I used the following input parameters and cuts

$$\alpha = 1/128, \quad \sin^2_\theta = 0.2224, \quad \alpha_s = 0.1$$
$$M_W = 80.41\ GeV, \quad M_t = 176\ GeV$$

$$
\begin{aligned}
&\Gamma_W = 2.1185\ GeV, \quad \Gamma_t = 1.6429\ GeV \\
&E_T(\nu_l),\ E_T(l^+),\ E_T(b),\ E_T(\bar{b})\ >\ 15\ GeV, \\
&|\eta(l^+)|,\ |\eta(b)|,\ |\eta(\bar{b})|\ <\ 2, \quad \Delta R(b\bar{b}) > 0.7\ ,
\end{aligned} \tag{5}
$$

together with the cone jet-definition algorithm of ref. [17] (with jet cone size $R=$ 0.7) and the CTEQ2M parton densities of ref. [18]. Two jets with b content are required to be present in the visible region defined by the above cuts, and no extra (gluonic) jets. I chose the lowest order values for Γ_W and Γ_t in order to get the right on-shell result when numerically rescaling $\Gamma_{W,t}$ and the cross section by the same amount.

In fig. 4 and 5, I show H_T and m_{bl} in the off-shell case and in the on-shell limit, including all final state gluonic corrections. As one can see, the effect of producing an off-shell top is mainly a different normalization factor with respect to the on-shell case.
In fig 6. the off-shell top invariant mass distribution is shown with and without final state QCD corrections. QCD radiation is responsible for a distortion in the Breit-Wigner distribution: more events are produced in the left tail and less in the right side, but the position of the peak is essentially unchanged. A similar distortion is also present in m_{bl} (compare the dotted line with the histograms in fig. 7). A quantitative knowledge of this effects may be useful in fitting the experimental distributions.
In on-shell production, the cross section (with the cuts and input parameters of eq.(5), including final state QCD corrections) is 0.02677 ± 0.00025 pb and reduces to 0.02433 ± 0.00011 pb for off-shell top. That means 10% less events. However, QCD corrections lowers the top width from the value in eq.(5) to $\Gamma_t = 1.5117\ GeV$, so that the cross section, using this new value for Γ_t, goes back to 0.02681 ± 0.00024 pb [1] , and, for example, the on-shell and off-shell m_{bl} distributions become almost indistinguishable (see again fig. 7).
As already discussed in the introduction, the question of the total number of produced events is important when looking at the single top production rate in this channel for new physics searches.

[1] This enhancement is, of course, a very well known phenomenon: see, for example, ref. [19].

4 Conclusions

I have performed a complete one loop calculation of the final state QCD corrections to the single top production process $\bar{d}\, u \rightarrow \nu_l\, l^+\, b\, \bar{b}$ in the off-shell case. Taking into account the widths of the particles lowers the cross section, but QCD corrections to Γ_t give a contribution in the opposite direction. Furthermore, final state gluonic radiation is responsible for a distortion in the distributions useful for top mass reconstruction.

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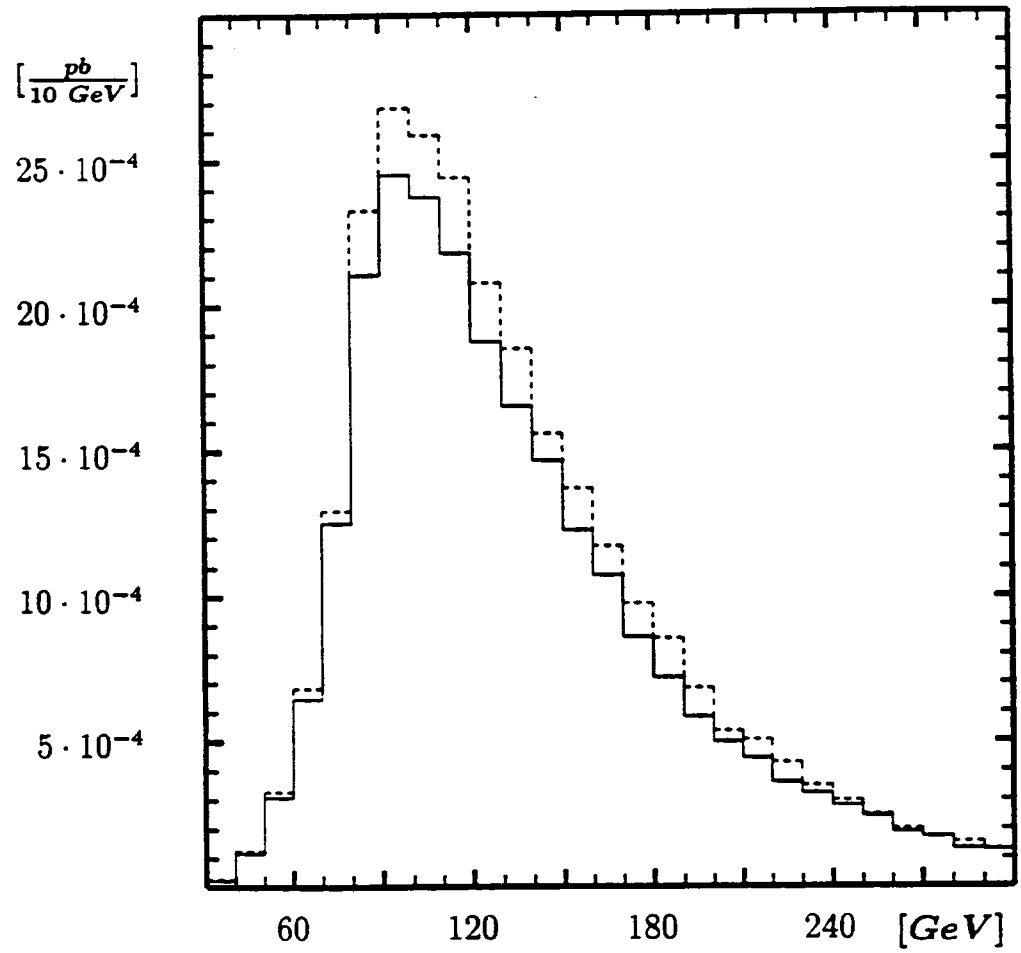

Figure 4: *Total hadronic transverse energy for on-shell (dashed line) and off-shell (solid line) single top production. Final state QCD corrections included.*

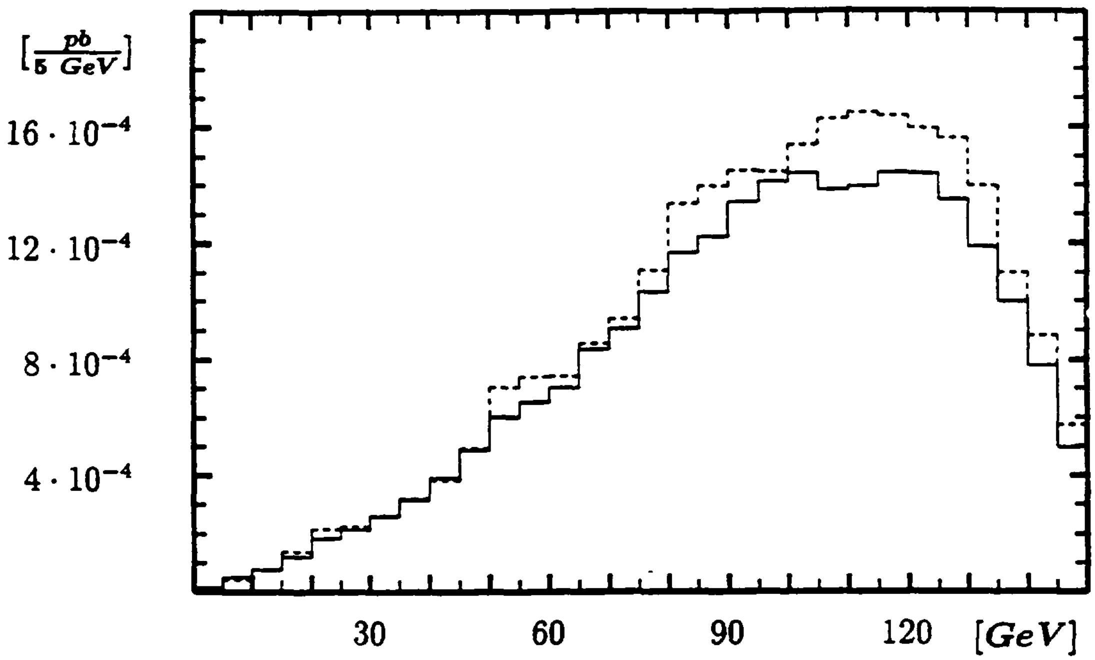

Figure 5: *Invariant mass of $l^+ + b$ for on-shell (dashed line) and off-shell (solid line) single top production. Final state QCD corrections included.*

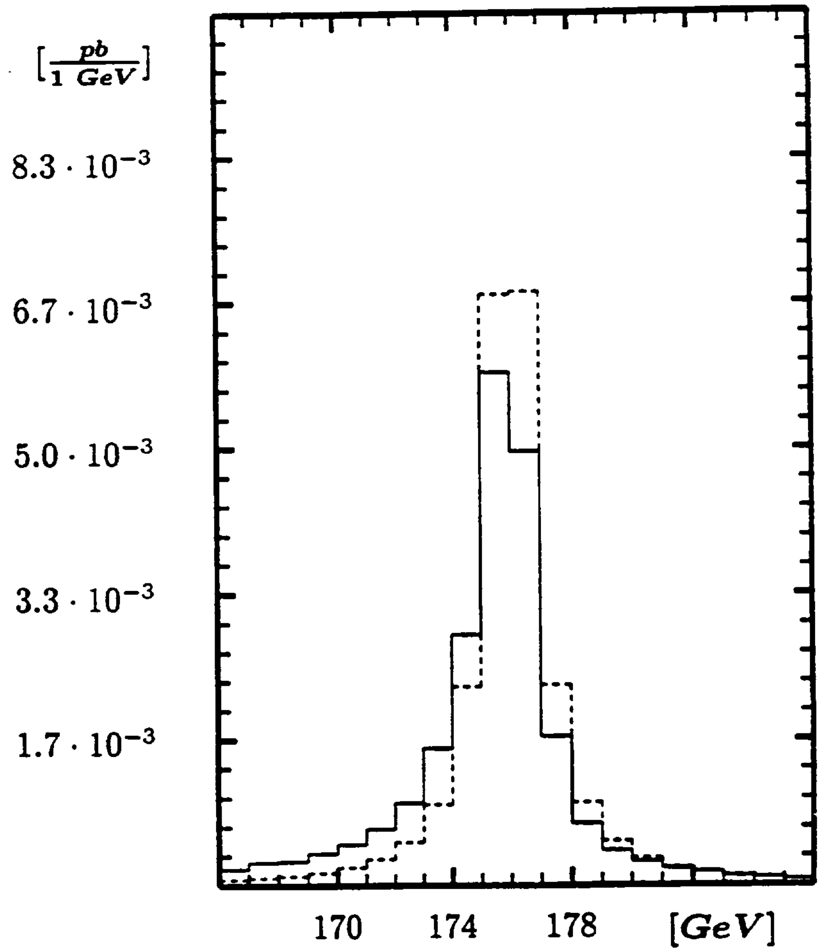

Figure 6: *Invariant mass of $l^+ + b + \nu_l$ for off-shell single top production, at the tree level (dashed line) and including final state QCD corrections (solid line).*

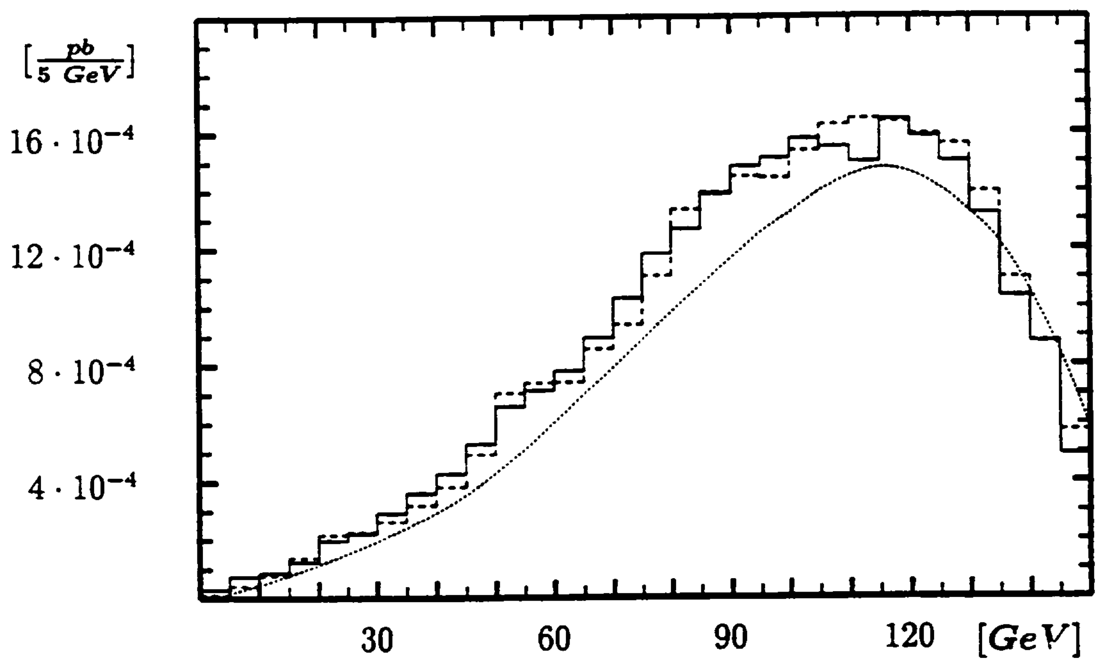

Figure 7: *The histograms are the invariant mass distribution of $l^+ + b$ for on-shell (dashed histogram) and off-shell (solid histogram) single top production, including final state gluonic corrections. In the off-shell case, the QCD corrected value of Γ_t is used. The dotted line is the off-shell tree level result ($\alpha_s = 0$).*